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# Experimental test of $^3\text{He}$ neutron-spin filter in MIEZE spectrometer

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**Abstract.** A modulated intensity by zero effort (MIEZE) spectrometer is a type of neutron-resonance spin-echo spectrometer and can be used to analyze the slow dynamics of condensed matter by measuring the intermediate scattering function  $I(Q, \tau)$ . A crucial feature of a MIEZE spectrometer is it leaves completely free the space between the sample and the detector because the sample is placed after the neutron-spin analyzer. Measuring the magnetic dynamics with a conventional neutron-spin-echo spectrometer is difficult, but with a MIEZE spectrometer such a measurement may be done simply by introducing a second analyzer after the sample. Measuring the magnetic dynamics with high precision requires the background to be reduced to a minimum and is a job for which a  $^3\text{He}$  neutron-spin filter ( $^3\text{He}$ -NSF) is a promising candidate as a second analyzer. However, one difficulty with this approach is the diffusion of  $^3\text{He}$  gas from the  $^3\text{He}$ -NSF, which may be measured and interpreted as dynamics. Therefore, we investigate herein whether the dynamics of gas diffusion is detected when using a  $^3\text{He}$ -NSF as second analyzer in a MIEZE spectrometer. Toward this end, we experimented with the MIEZE spectrometer installed at beamline 06 (BL06) at the Materials and Life Science Experimental Facility at Japan Proton Accelerator Research Complex (J-PARC MLF). The results confirm that the gas-diffusion dynamics of the  $^3\text{He}$ -NSF are not detected, and that the  $^3\text{He}$ -NSF, therefore, can be used as a second analyzer in this MIEZE spectrometer.

## 1. Introduction

A MIEZE spin-echo spectrometer is a type of resonance spin-echo spectrometer. As with conventional spin-echo spectrometers, it offers high energy resolution and is a powerful tool for studying slow dynamics in condensed matter because it can measure the intermediate scattering function  $I(Q, \tau)$ , where  $Q$  and  $\tau$  are the momentum transfer of neutrons and the Fourier time, respectively [1–3]. In Japan, the technical development of MIEZE-type spectrometers was done at the research reactor facility JRR-3, but recently a MIEZE spectrometer was installed at BL06 at J-PARC MLF.

Because both  $Q$  and  $\tau$  depend on the neutron wavelength, measurement of a wide  $Q$ - $\tau$  range is possible at one time by using a pulsed neutron beam, which significantly improves the measurement



efficiency. At BL06 at the J-PARC MLF, combination of a MIEZE spectrometer and the time-of-flight method (TOF-MIEZE) has already been implemented and demonstrated, and the user program will start soon [4, 5]. The distinguishing characteristic of the MIEZE spectrometer is the sample is placed downstream of the neutron-spin analyzer.

Despite being essentially a spin-echo spectrometer, this system makes it is easy to measure magnetic materials, and it is particularly effective for research in the field of magnetic dynamics. Furthermore, polarization analysis becomes possible by installing a second neutron-spin analyzer after the sample (called the “second analyzer”), which allows polarization analysis to be applied to the study of spin dynamics [6]. Candidates for the second analyzer include a multilayered magnetic supermirror and a  $^3\text{He}$  neutron-spin filter ( $^3\text{He}$ -NSF). However, the multilayered polarized mirror produces background due to diffuse scattering, whereas scattering from  $^3\text{He}$  is less than that from the magnetic supermirror. Scattering from a  $^3\text{He}$ -NSF, depending on the thickness of the glass cell, is on the order of  $10^{-4}$ , which is lower than the diffuse scattering of a typical supermirror [7]. Therefore, a  $^3\text{He}$ -NSF is considered useful for background reduction. However, the  $^3\text{He}$ -NSF contains a glass cell filled with  $^3\text{He}$  gas. Therefore, if diffusion of the  $^3\text{He}$  gas is detected and, therefore, contributes to the dynamical signal, it would create a background in the magnetic dynamics data. For example, the relaxation time can be estimated to be on the order of tens of picoseconds around  $Q = 10^{-4} \text{ \AA}^{-1}$ , which is near the direct beam. This may match the Fourier time range of the MIEZE spectrometer, and may be detected as dynamics. Therefore, we measured in this study the MIEZE signal with and without the  $^3\text{He}$ -NSF as second analyzer to investigate whether the diffusion of  $^3\text{He}$  gas is detected.

## 2. Experiment setup

Figure 1 shows a schematic of the MIEZE spectrometer and energy diagram at BL06 at the J-PARC MLF. Upstream of the diagram is a neutron-spin polarizer, and the diagram shows two resonance spin flippers (RSF1 and RSF2), followed by a neutron-spin analyzer and a detector. A guide field coil extends from the polarizer to the analyzer (not shown in the diagram). No magnetic field exists between the sample and detector, and the second analyzer (e.g., the  $^3\text{He}$ -NSF) can be installed in this space to analyze the polarization.

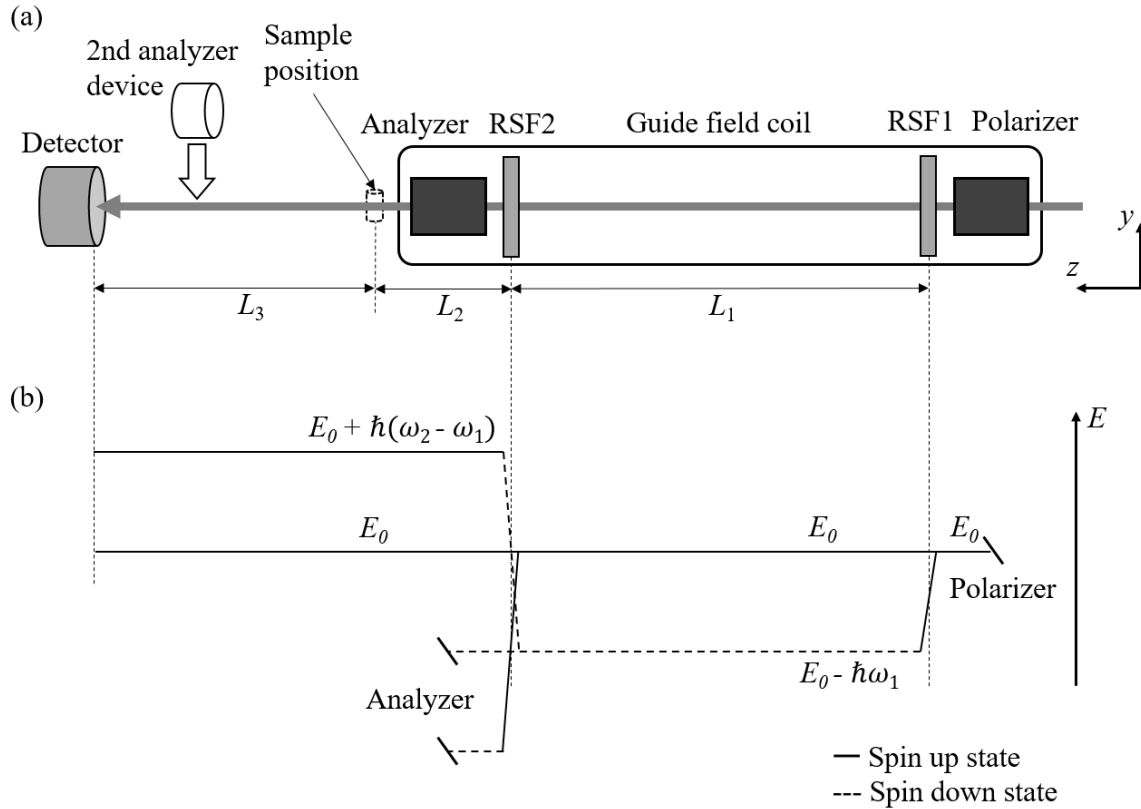


Figure 1. (a) Conceptual and (b) energy diagram of MIEZE-type spectrometer at BL06 at the J-PARC MLF.

RSF1 is a single coil resonant spin flipper operating with  $\pi/2$  condition, and in order to work with pulsed neutrons, the amplitude of the oscillating magnetic field is modulated depending on  $1/t$ , where  $t$  is the TOF to the RSF1. The driving frequency of the oscillating magnetic field is  $\omega_1$ , and an energy difference  $\Delta\omega_1$  occurs between up and down neutron spin states. RSF2 is also a single coil resonant spin flipper, and the amplitude of the oscillating magnetic field is modulated to  $1/t$ . The driving frequency of the oscillating magnetic field is  $\omega_2$ . In the analyzer, only the spin-up state is selected, and the neutron intensity  $I_d$  and total phase difference  $\Phi(t_d)$  at the detector are expressed as a function of time at the detector  $t_d$ .

$$I_d(t_d) = \frac{1 + \cos\Phi(t_d)}{2} \quad (1)$$

$$\Phi(I_d) = (\omega_2 - \omega_1)t_d - \frac{\omega_1}{v}L_1 + \frac{\omega_2 - \omega_1}{v}(L_2 + L_3) \quad (2)$$

where  $v$  is the velocity of neutron, and  $L_1, L_2, L_3$  are the distance between RSF1 and RSF2, RSF2 and sample, and sample and detector, respectively. In the spin echo condition,  $\omega_1 L_1 = (\omega_2 - \omega_1)(L_2 + L_3)$ , in which the phase difference depending on the flight path is canceled, Eq. (2) becomes  $\Phi(t_d) = (\omega_2 - \omega_1)t_d$ . The energy resolution of the MIEZE spectrometer is also determined by the Fourier time,  $\tau$ , given by

$$\tau = \frac{(\omega_2 - \omega_1)\hbar L_3}{mv^3} \quad (3)$$

In this experiment,  $\omega_1$  and  $\omega_2$  were operated with the conditions of 0.2 MHz and 0.4 MHz, respectively, for an effective frequency  $\omega_2 - \omega_1$  of 0.2 MHz, and  $L_1$ ,  $L_2$ ,  $L_3$  were about 2.0 m, 0.7 m, 1.3 m.

The experiment was done at the MIEZE spectrometer installed in BL06 VIN ROSE at the J-PARC MLF. Figure 2 shows a photograph and a schematic diagram with the  $^3\text{He}$ -NSF in the MIEZE spectrometer. As shown in Fig. 1, the  $^3\text{He}$ -NSF was installed in the free area just upstream of the detector. A glass cell filled with  $^3\text{He}$  gas was placed in a uniform magnetic field generated by a solenoid coil to maintain the  $^3\text{He}$  nuclear-spin polarization. The glass cell measured 35 mm in diameter and 55 mm in length, and the  $^3\text{He}$  gas pressure was 2 bar (effective gas-pressure-length was 11 bar cm).

Before entering the MIEZE spectrometer, the  $^3\text{He}$  nuclear spin was polarized by using spin exchange optical pumping (SEOP), which gave 60%  $^3\text{He}$  nuclear-spin polarization [8]. The relaxation time of the  $^3\text{He}$  nuclear-spin polarization was 75 hours. As shown in Fig. 1(b), the guide magnetic field of the MIEZE spectrometer was 6 Oe in the  $-y$  direction and the magnetic field of the solenoid coil with the  $^3\text{He}$ -NSF was 15 Oe in the  $+z$  direction. At the position of the  $^3\text{He}$  cell, the leakage magnetic field due to the guide magnetic field of the MIEZE spectrometer was 1 to 2 Oe in the  $+y$  direction. Therefore, we started by investigating how this leakage magnetic field affected the relaxation time of  $^3\text{He}$  nuclear spin.

Figure 3 shows the relaxation time measured by using adiabatic-fast-passage nuclear magnetic resonance (AFP-NMR) technique [9]. The vertical axis is the voltage of the NMR signal, and the horizontal axis is time. The results give 68 h as the relaxation time. Although the relaxation time is slightly less than 75 h, which was measured previously in the SEOP laboratory, it is deemed adequate for practical use.

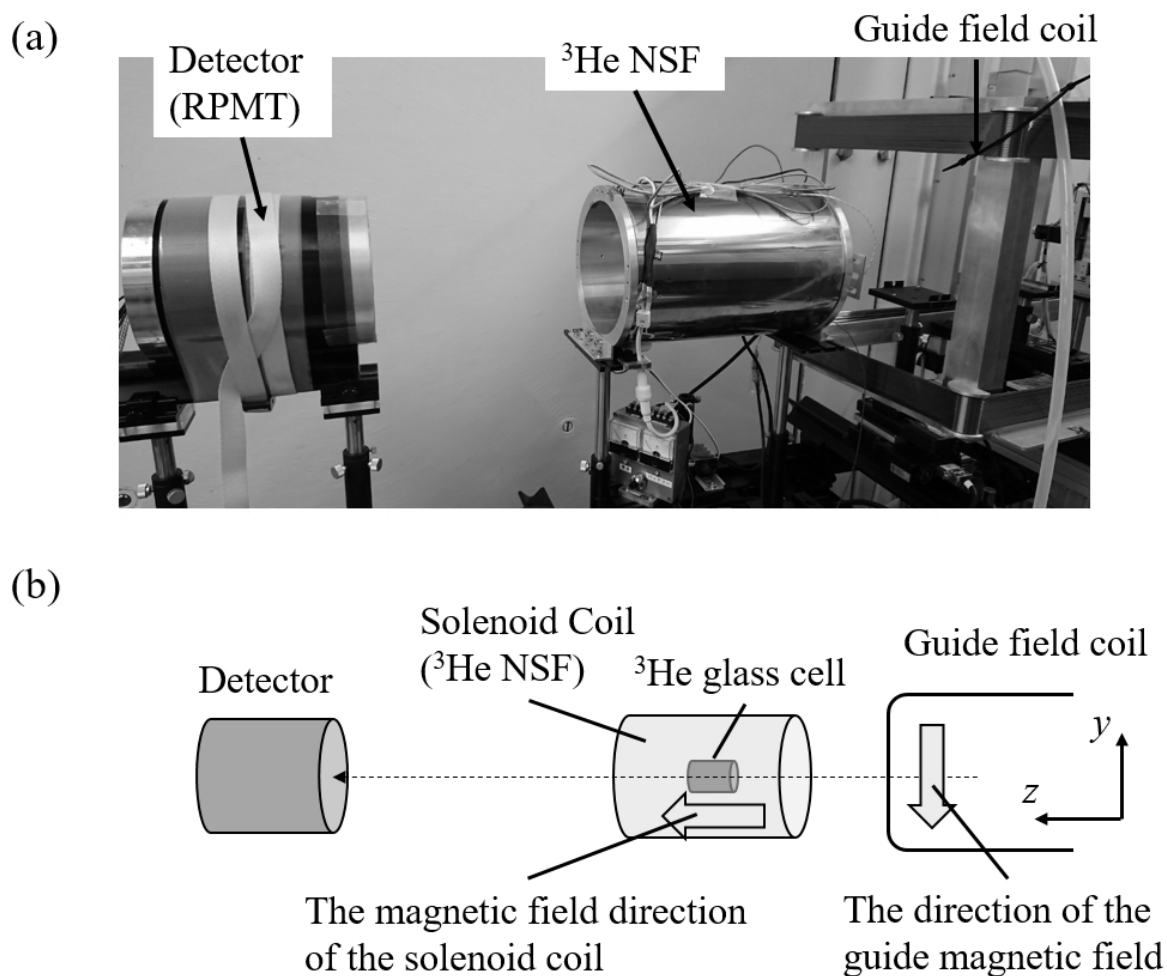


Figure 2. (a) Photograph of experiment using  $^3\text{He}$ -NSF in MIEZE spectrometer at BL06 of the J-PARC MLF. (b) Schematic diagram showing components of MIEZE spectrometer around the second analyzer, and the coordinate system and magnetic field.

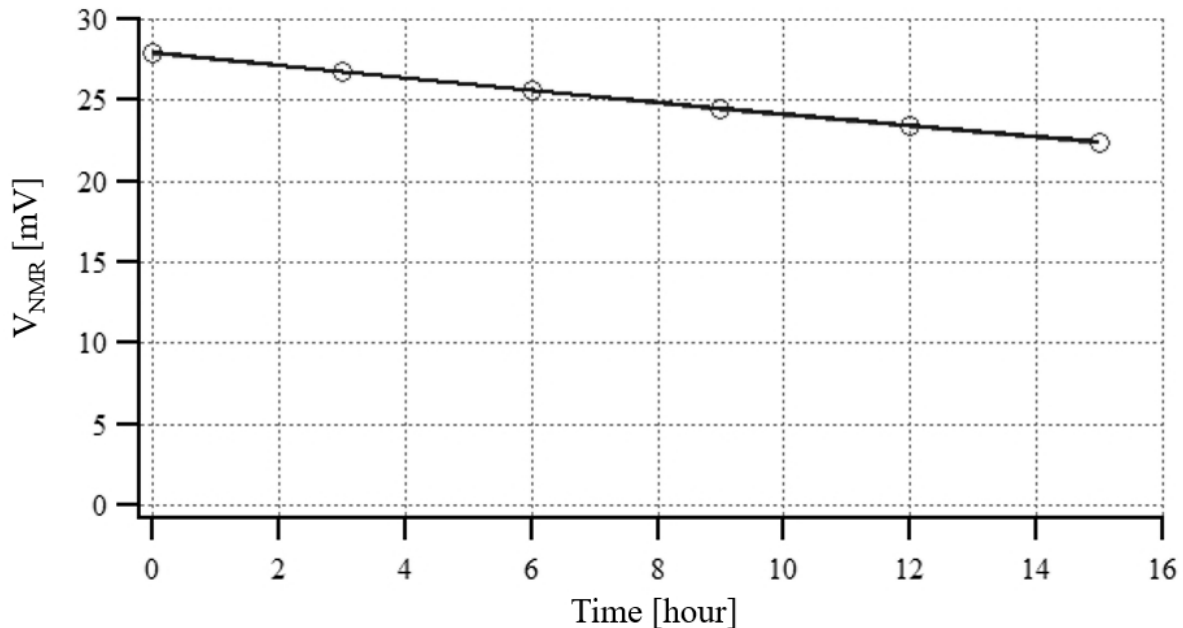


Figure 3. Relaxation of polarized  $^3\text{He}$  nuclear spins as measured by the AFP-NMR technique.

### 3. Results

Before observing the MIEZE signal, we ensured that the guide magnetic field of the MIEZE spectrometer and the magnetic field of the solenoid coil of  $^3\text{He}$ -NSF were adiabatically connected for polarized neutrons. By using the AFP-NMR technique, the direction of  $^3\text{He}$  nuclear spin can be set as parallel or antiparallel with respect to the magnetic field of the solenoid coil [9], which means that we measured the beam intensities  $I_+$  and  $I_-$  (i.e., the parallel and antiparallel components, respectively, with respect to the guide magnetic field). Thus, we obtained the neutron polarization, which is defined by  $P_N = (I_+ - I_-)/(I_+ + I_-)$ , as a function of TOF (see Fig. 4). Were the magnetic field connection not adiabatic for polarized neutrons, the neutron spin would rotate about the axis of the guide magnetic field, and the neutron polarization  $P$  would oscillate periodically with TOF. However, no such periodic oscillations appear in Fig. 4. This result shows that the guide magnetic field of the MIEZE spectrometer and the magnetic field of the solenoid coil of the  $^3\text{He}$ -NSF were adiabatically connected for polarized neutrons.



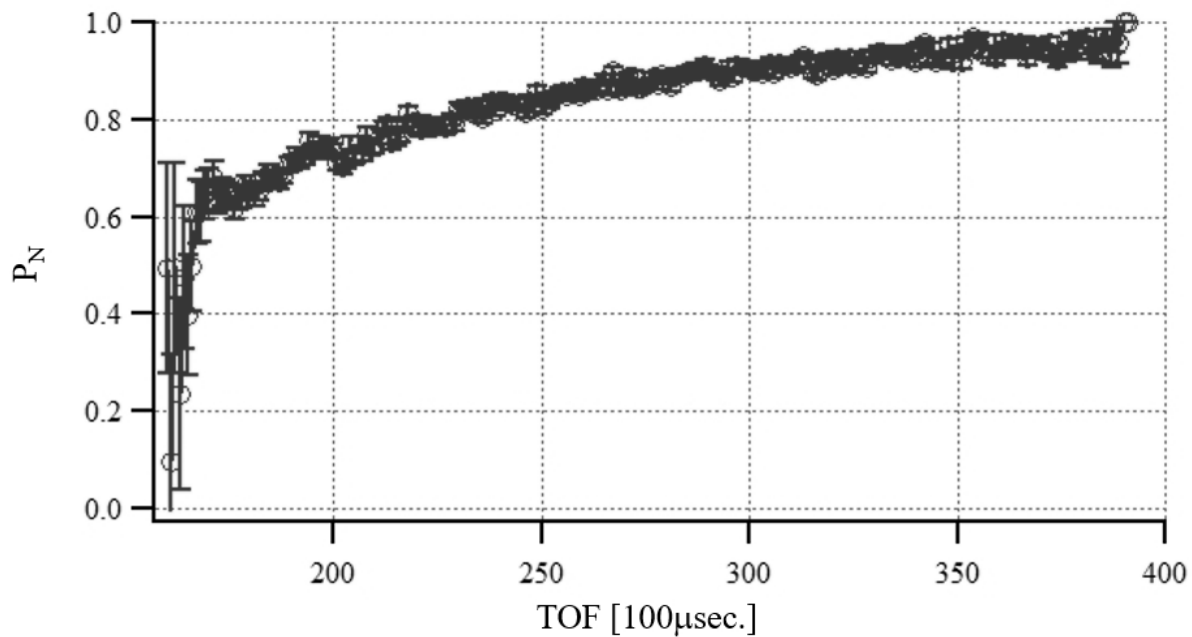


Figure 4. Measured neutron polarization  $P$  as a function of neutron TOF.

Once the magnetic field connection was confirmed, measurement of the MIEZE signal was performed. For this measurement, the effective frequency of the MIEZE signal was set to 0.2 MHz. Figures 5(a) and 5(b) show the MIEZE signal with and without the  $^3\text{He}$ -NSF, respectively. Figure 5(c) [5(d)] shows an expanded view of the time range 20 000–20 050  $\mu\text{s}$  from Fig. 5(a) [5(b)]. Figures 5(c) and 5(d) both show an oscillatory beat signal with respect to TOF. These MIEZE signals were then fit to

$$f(t) = a \cos(\omega t + \phi) + b \quad (4)$$

to obtain the visibility, which is defined as  $a/b$ . Table I gives the parameter values resulting from these fits and the resulting visibility.

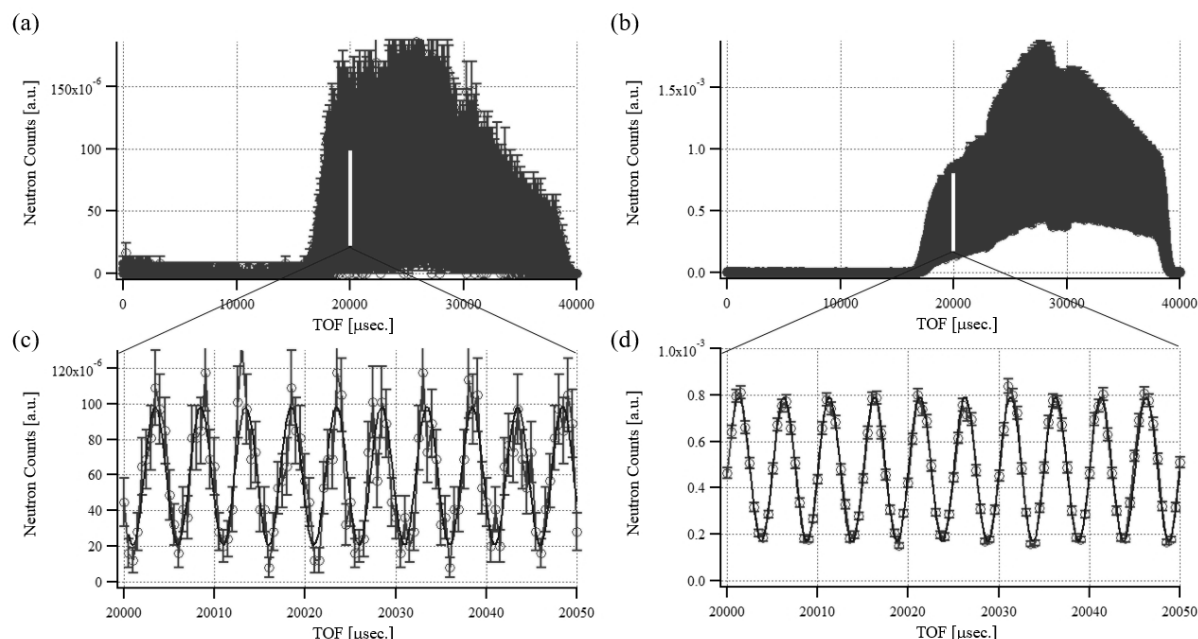


Figure 5. (a), (b) Measured results of MIEZE signals with and without  $^3\text{He}$ -NSF. (c), (d) Enlarged view of data from panels (a) and (b), respectively.

Table I. Results of fitting MIEZE signals to Eq. (4) and the resulting visibility.

Coefficients	with $^3\text{He}$ NSF	without $^3\text{He}$ NSF
$a$	$3.8849 \times 10^{-5} \pm 2.14 \times 10^{-6}$	$3.1195 \times 10^{-4} \pm 3.54 \times 10^{-6}$
$b$	$5.9423 \times 10^{-5} \pm 1.51 \times 10^{-6}$	$4.806 \times 10^{-4} \pm 2.51 \times 10^{-6}$
$\omega$	$0.2 \pm 0.00061$ MHz	$0.2 \pm 0.000124$ MHz
Visibility	$0.6537 \pm 0.0397$	$0.6491 \pm 0.0081$

As shown in Table I, the frequency  $\omega$  of the MIEZE signal with and without of the  $^3\text{He}$ -NSF is 0.2 MHz, which is consistent with the RSF operating condition. In addition, the visibility for each MIEZE signal with and without the  $^3\text{He}$ -NSF is about 0.65.

For this measurement, the distance between the  $^3\text{He}$ -NSF and the detector was about 0.5 m. In the fitting region of Figs. 5(c) and (d), the neutron wavelength corresponding to a TOF of 20000  $\mu\text{sec}$  is 3.5  $\text{\AA}$ , and the Fourier time for an effective frequency of 0.2 MHz and a sample ( $^3\text{He}$ -NSF) to detector distance of 0.5 m is estimated from Eq. (3) to be about 30 picoseconds. This matches the relaxation time range of  $^3\text{He}$  gas in the  $Q$  range near the direct beam. From the results shown in Fig. 5 and Table 1, however, the visibility of the MIEZE signal did not change with and without the  $^3\text{He}$ -NSF. This is considered to be because the scattering from  $^3\text{He}$  gas (including glass cell) is as low as  $10^{-4}$  order, and therefore, it did not affect the visibility of the MIEZE signal.

On the other hand, Fig. 5 (a) and (b) show that the statistics with the  $^3\text{He}$ -NSF are clearly lower than those without the  $^3\text{He}$ -NSF. This is due to the low transmittance of the neutron beam through the  $^3\text{He}$ -NSF. Under the conditions of 11 bar cm of gas pressure-length and 50 % of  $^3\text{He}$  nuclear-spin polarization, the transmission was quite low at about 10 % for neutrons with a wavelength of 3.5  $\text{\AA}$ . (The low value of the  $^3\text{He}$  nuclear-spin polarization of 50 % was due to the fact that the MIEZE signal measurement was carried out after the  $^3\text{He}$  relaxation time measurement shown in Fig. 3.) Cell development is an important issue for the future, including optimization of gas pressure-length and improvement of  $^3\text{He}$  nuclear-spin polarization.

#### 4. Conclusion

This study verifies whether a  $^3\text{He}$ -NSF can be used as a second analyzer in the MIEZE spectrometer in BL06 of the J-PARC MLF. Before doing this experiment, we investigated how the leakage magnetic field from the guide magnetic field of the MIEZE spectrometer affects the relaxation of  $^3\text{He}$  nuclear spin, and found that the relaxation time was reduced from 75 to 68 h, which is a weak effect. However, we confirmed that the performance of the  $^3\text{He}$ -NSF was sufficient for practical use. Then, we measured the MIEZE signal with and without the  $^3\text{He}$ -NSF in the beamline and compared the results. This comparison reveals no difference in visibility between the MIEZE signal with the  $^3\text{He}$ -NSF and that without the  $^3\text{He}$ -NSF, which demonstrates that the diffusion of  $^3\text{He}$  gas does not affect the MIEZE signal. Thus, we conclude that the  $^3\text{He}$ -NSF may be used as a second analyzer in the MIEZE spectrometer.

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